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Design Fires for Vehicles in Road Tunnels

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ABSTRACT

Fire in road tunnels is a unique design problem which can lead to serious consequences if not addressed appropriately. Observations from full scale tunnel fire experiments have indicated the heat release rate depends on the ventilation conditions, tunnel geometry and fuel load. Although these experiments have provided valuable information, they are generally very expensive to conduct and the data are limited. The experiments are often based on a specific test condition such as air velocity, geometry or tunnel slope which may be different from the design conditions present for an actual tunnel project.

The design of smoke extraction systems for tunnels often uses prescriptive values for the heat release rate (HRR) from a vehicle fire which does not account for the tunnel conditions. This paper presents an overview of the methodology to estimate the heat release rate of a credible vehicle fire in a road tunnel using a performance-based approach. The analysis consists of two stages; stage one involves the use of a probabilistic approach (risk analysis) to identify the potential cause and type of vehicle which could result in a tunnel fire. Findings from the risk analysis are used in stage two in which Computational Fluid Dynamics (CFD) modelling is used to establish the heat release rate in a tunnel considering factors such as fuel load, ventilation condition, tunnel geometry and ignition location. An urban tunnel in Singapore is used to illustrate this methodology.

INTRODUCTION

In a tunnel fire incident, creating a smoke free path for motorist evacuation and facilitating fire fighters to access the fire is critical for fire and rescue operations. A means of achieving this is to use ventilation fans to blow sufficient air down the tunnel ensuring no back-layering of smoke occurs upstream of the fire. The airflow necessary for such operation is known as the critical velocity [1]. The critical velocity is a function of a number of factors which includes the heat release rate, tunnel gradient and tunnel geometry [1]. In a longitudinal tunnel ventilation system, the design is considered acceptable if the system design velocity is higher than the calculated critical velocity. A one-dimensional analytical tool such as Subway Environmental Simulation (SES), Road Tunnel Ventilation (RTV) or TUNVEN can be used to establish the system design velocity. Based on the critical velocity equations, a higher heat release rate in the tunnel would require higher airflow to meet the system design performance [2]. From a fire and life safety design point of view, it is clear that the heat release rate in the tunnel plays an important role in tunnel the ventilation requirements as inappropriate selection of a design fire could result in a system that is insufficient.

The type of vehicles, number of vehicles and the type of goods carried by these vehicles can vary considerably resulting in different heat release rate output. Vehicles on the road can vary from motorcycles to heavy goods vehicles or even a petrol tanker. In the event of a tunnel fire, the magnitude of their heat release rate can be quite different. It is also feasible that in an extreme fire scenario where up to several tens or hundreds of vehicles could be involved in a severe collision resulting in a catastrophic incident. For design applications, the choice of a design fire often corresponds to the traffic flow expected for a particular tunnel. This is because the material which burns in a road tunnel mostly comes from vehicles involved [3]. Recommendations from various guidelines such as NFPA 502 [4], BD78/99 [5] and PIARC technical committee report [2] are often used as a basis in incorporating the expected traffic flow of a tunnel to determine the design fire. From Table 1, the heat release rate can range from 2.5 MW to 5 MW for a passenger car and 20 MW to 30 MW for a heavy goods vehicle. However, recent fire experiments [6] conducted in the Runehamar Tunnel show that larger vehicles with burning goods may cause a higher output (approx 67 MW to 200 MW peak). These experiments suggest that heat release rate guidelines regarding heavy goods vehicles are currently underestimated.

| Guidelines | NFPA 502 (2004)⁴ | BD 78/99⁵ | PIARC² |
|--------------------------|------------------------------------|-------------------------------|-------------------------------|
| <i>Type of fire load</i> | <i>Heat release rate (MW)</i> | <i>Heat release rate (MW)</i> | <i>Heat release rate (MW)</i> |
| Passenger car | 5 | 5 | 2 - 5 |
| Bus | 20 | 20 | 20 |
| Van | - | 15 | 15 |
| Heavy goods vehicle | 20 - 30 | 30 - 100 | 20 - 30 |
| Petrol tankers | 100 | - | - |

Table 1: Heat release rate information from various guidelines.

This paper provides an overview of the challenges faced in establishing a design fire for road tunnels and introduces a methodology to estimate a credible vehicle fire in a road tunnel using a performance-based approach. The analysis consists using a probabilistic approach (risk analysis) to identify the potential cause and type of vehicle which could result in a tunnel fire based on

statistical data (e.g. traffic fleet, causes of vehicle fire). Fire scenarios identified from stage one of the risk analysis are modelled using CFD to establish the heat release rate considering factors such as fuel load, ventilation condition, tunnel geometry and ignition location. Figure 1 shows the overall approach involving the use of probabilistic approach coupled with deterministic approach to establish a design fire for road tunnel smoke control design.

PROBABILISTIC APPROACH (FIRE RISK ANALYSIS)

In stage one of the analysis, fire risk level is used as a criterion to identify the potential fire scenarios that could occur in the tunnel. In its simplest form, fire risk can be represented as [7] $Fire\ Risk = Probability \times Consequence$ where the probability component is the likelihood of various causes of fire and the consequences component is obtained from the fire growth characteristics such as the combustible material in the tunnel (e.g. systems in the tunnel or vehicles and their goods). Since the number of fire scenarios in a tunnel can be numerous, it is recognised that it is not possible to design a smoke control system for every potential incident.

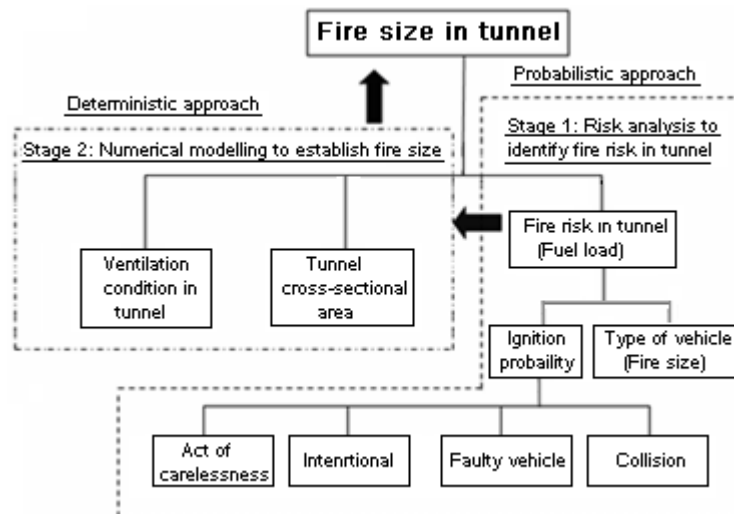


Figure 1: Approach to estimate fire size in tunnel.

The cost and practicality to design for extreme events is beyond what might be considered a reasonable worst case. Therefore, the selection of the design fire scenario has to be made on the basis of a risk analysis [8]. It is important to define the context and goals such that stakeholders (designers, tunnel operator, approving authority and fire service etc) are aware of the risk involved. The purpose of fire risk analysis will also allow stakeholders to identify, assess and treat these risks within all practical limits. Fault Tree Analysis is used to identify the fire risks in this tunnel. To formulate a logic diagram for tunnel fire risk analysis, it is important to consider the potential cause of a fire in a tunnel, the traffic condition in the tunnel and vehicle heat release rates.

Causes of vehicle fire

From past international tunnel fire incidents [3], the causes of road tunnel fire are generally originated from the vehicle itself. The factors that contribute to the cause of motor vehicle fire

can be divided into four categories; a faulty vehicle, an act of carelessness, arson and the aftermath of a collision [9]. Depending on the country and the location of the tunnel, the frequency of the vehicle fire incident data by cause can vary.

Vehicle classification

In Singapore, vehicle types are classified into motorcycles, cars, taxis, buses and goods vehicles [10]. For goods vehicles, they are further categorised into light goods vehicles (LGV), heavy goods vehicles (HGV) and very heavy goods vehicles (VHGV). The classification of goods vehicles is according to their laden weight where goods vehicles less than 3.5 tonne are categorised as LGV, vehicles with laden weight between 3.5 tonne to 16 tonne are HGV (e.g. a rigid truck) and vehicles more than 16 tonne are identified as VHGV (e.g. a tractor with trailer).

A particular concern is with transporting hazardous materials through tunnels and using legislation by restricting vehicles carrying hazardous material from entering the tunnel is an effective means to reduce the risk. However, restricting hazardous materials and placing controls on the actions of drivers will be ineffective unless accompanied by strict enforcement. According to the Singapore Road Traffic Act [11], VHGV and vehicles carrying hazardous materials are not allowed to enter any road tunnel. Measures such as the Hazmat Transport Vehicle Tracking System (HTVTS); a GPS device that allows the Singapore Civil Defence Force to track and remotely disable the engine of vehicle carrying hazardous materials are in place to enforce these regulations[12]. In view of regulatory requirements, the scenario of a VHGV or vehicles carrying hazardous materials in the tunnel are not considered in the risk analysis.

| Type of vehicle / test series | Peak HRR (MW) | Experimental conditions |
|--|-----------------------|-----------------------------------|
| Scooter ¹³ | 1.24 | Laboratory |
| Car ¹⁴ | 1.5, 1.8, 2 | Laboratory |
| Car ¹⁵ | 4.3, 8.5 | Canopy |
| Car ¹⁶ | 4.7 | Tunnel : u = 6 m/s |
| People mover ¹⁷ | 6 | Tunnel: u = 0.4 m/s |
| Bus ¹⁸ | 29.7 | Tunnel: u = 0.3 m/s |
| Simulated truck with rubber tyres, wood, plastic cribs ¹⁸ | 17 | Tunnel : u = 0.7 m/s |
| Simulated truck with wooden pallets, tyres, tarpaulin ¹⁶ | 13, 19, 16 | Tunnel : u = 0, 4 - 6 m/s & 6 m/s |
| Tractor with 2 ton of furniture ¹⁷ | 125 | Tunnel : u = 3 - 6 m/s |
| Trailer with different commodities ¹⁹ | 203, 158, 124.9, 70.5 | Tunnel : u = 3 m/s |

Table 2: Heat release rate from various fire experiments (u – air velocity in the tunnel, m/s).

Vehicle heat release rate

The consequence or the heat release rate of the vehicle plays an important role on the outcome of the risk analysis. Higher consequences (higher heat release rate) would result in higher fire risk. There have been several fire test programmes carried out by researchers in which the fire characteristics and magnitude of a vehicle fire in a tunnel and non-tunnel environments have been measured. Depending on the type of vehicle involved, the quantity of the fuel package, tunnel geometry and ventilation condition, the vehicle heat release rate varies from 0.5 MW to 203 MW (Table 2). Therefore the criteria of selecting a heat release rate for risk analysis should be based on these factors.

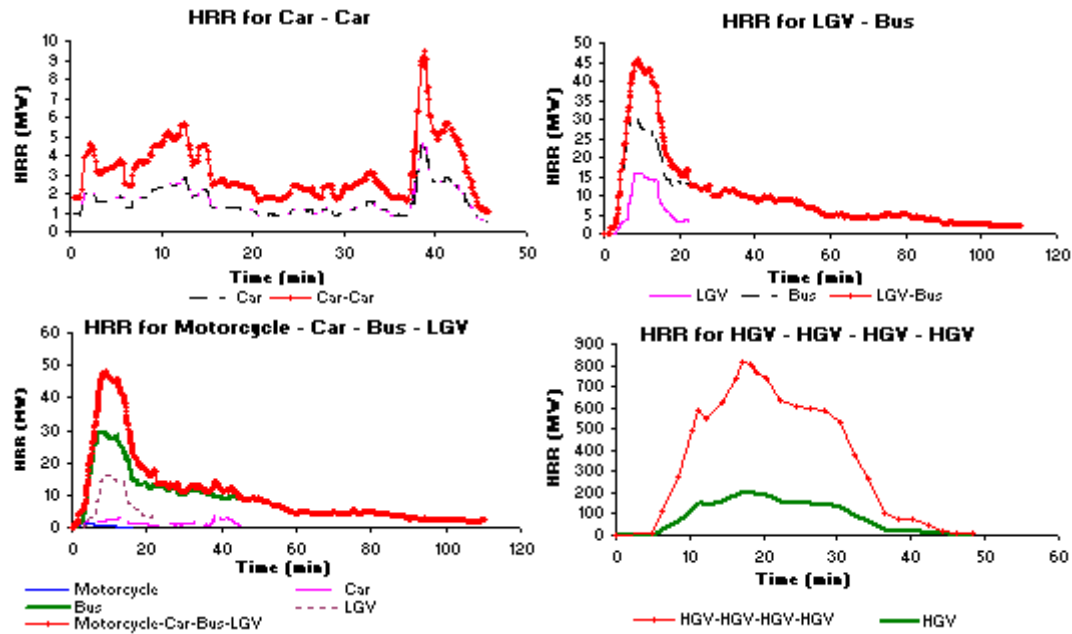


Figure 2: Example of heat release rate curves for vehicle fires involving multiple collisions.

Fire scenarios involving multiple vehicles fire are generally not available in the literature. Given the current knowledge, the heat release rate used for a fire scenario involving a multiple-vehicle collision assumes all incident vehicles ignite at the same time and the peak heat release rate is the sum of the individual vehicle heat release rates taken from a single vehicle experiments (Figure 2). This assumption is likely to provide a more conservative estimate as compared to the situation where fire is considered to propagate from one vehicle to another.

Tunnel fire risk analysis

A fault tree logic diagram for estimating the fire risk level is illustrated in Figure 3. The numerical data for the vehicle fleet expected to use this tunnel, statistics on causes of vehicle fire and vehicle collision statistic obtained from the Land Transport Authority of Singapore, Singapore Civil Defence Force and the Singapore Traffic Police and were used in the fire risk calculation [8].

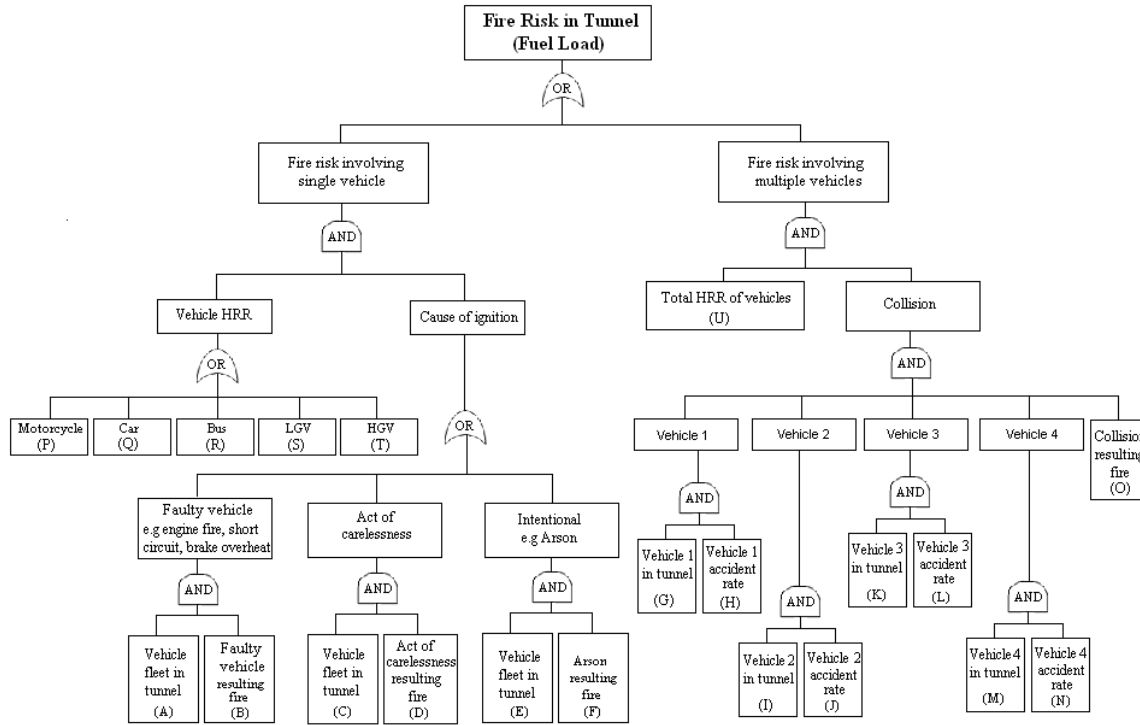


Figure 3: Fault tree logic diagram for fire risk in tunnel.

For this tunnel, it was found that a light goods vehicle (LGV) has a higher fire risk level in the tunnel as compared to other types of vehicle. Multiple vehicle collision involving four buses has the lowest fire risk level (Table 3). The low fire risk level concerning collision of buses resulting in fire is attributed to the low bus traffic expected in this tunnel and the relatively low bus accident rate in Singapore.

| Type of potential fire risk | Vehicle fault | Carelessness | Intentional | Collision |
|-----------------------------|-----------------------|-----------------------|-----------------------|------------------------|
| Maximum exposure risk: | 8.14×10^{-4} | 1.70×10^{-4} | 3.72×10^{-4} | 1.39×10^{-6} |
| Vehicle configuration: | Single LGV | Single LGV | Single LGV | Single HGV |
| Minimum exposure risk: | 4.93×10^{-6} | 1.03×10^{-6} | 2.25×10^{-4} | 6.40×10^{-21} |
| Vehicle configuration: | Single Bus | Single Bus | Single Bus | Bus-Bus-Bus-Bus |

Table 3: Summary of potential fire risk (urban tunnel in Singapore).

Although the expected frequency of cars traversing in this tunnel is higher than LGVs, the fire risk level for a car fire is lower in view of their lower peak heat release rate. Similarly for HGV, the higher peak heat release rate of a HGV does not contribute a higher fire risk level considering the small number of HGVs expected in the tunnel. Through this method, the measure of fire risk provides direction in finding a reasonable worse case fire allowing further numerical analysis to be carried out to establish the heat release rate in a tunnel. A single HGV and a single LGV were selected for the subsequent numerical analysis work.

DETERMINISTIC APPROACH (CFD SIMULATION)

The second portion of the work provides an outline on the factors that need to be considered when predicting the heat release rate in a road tunnel using a numerical approach. The FDS (version 4.0.7) CFD model of fire-driven fluid flow is used for the analysis. As with any complex fuel assembly configuration, modelling a goods vehicle fire using FDS to estimate the heat release rate in a tunnel is a challenging task. To enhance the confidence in using CFD to estimate the initial fire growth and peak heat release rate, work to develop a simplified representation of wood and plastic pallets burning in the tunnel and illustrate that the simulation model is able to reproduce a reasonable estimate of the fire characteristics were performance using one of the Runehamar tunnel fire experiments. The heat release rate is estimated using the HHRPUA from cone tests and a surface burning factor is incorporated in the simulation to ensure fuel load area model in the simulation is equivalent to the fuel load used in the actual experiments. Although similar growth rate history and peak heat release rate (6% different) were produced from the simulation, the current model is unable to simulate phenomena such as collapse of the fuel package. This is observed in the decay phase of the fire development (Figure 4) [20].

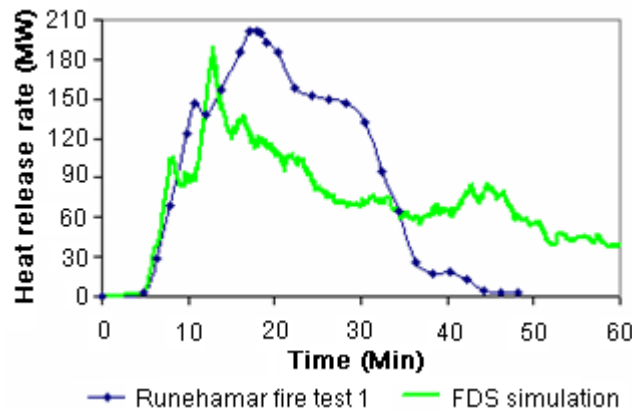


Figure 4: Comparison of FDS and Runehamar fire experiment.

Fuel load

To realistically estimate a design fire in the tunnel, it is important to know the general fire risk in a tunnel as larger fuel quantity would result in higher heat release rate. This is evident in the Runehamar Tunnel Fire Test [19]. From the fire risk analysis established in stage one, a single HGV fire or a single LGV fire had identified as the potential fire risk scenarios. Therefore, subsequent numerical work is based on these two scenarios to establish the design fire for this tunnel. However, the amount of fuel load a goods vehicle can carry is dependent on the goods vehicle category. Goods vehicles of higher category are generally larger in size and are capable of carrying larger loads. Although goods vehicles are categorised according to their laden weight, the dimensions of a LGV or a HGV varies depending on the manufacturer's specification. Typical goods vehicles found on the Singapore road network were selected for this analysis. The vehicle deck dimensions used are 3.1 m (length) by 1.6 m (width) for LGV and 8.2 m (length) by 2.3 m (width) for HGV. There is also requirement in Singapore where HGV with height more than 4.5 m is not allowed to enter the tunnel [11] and for light goods vehicle, the maximum canopy installation height should not be more than 3.2 m [21]. Another factor that affects the heat

release rate is the type of commodity (e.g. wood, plastic) carried by the goods vehicle. As information on commodity transport by road in Singapore is not available, data from other countries were used. Based on Swedish statistics and professional goods transport agents, a 80% cellulose and 20% plastic fuel load is a reasonable division to allocate goods transport on the road [19]. Like Sweden, Singapore is a well developed country where the daily transportation of products is likely to be similar in nature; therefore it is a reasonable assumption to use data from Sweden for this analysis.

Components of the vehicle chassis and truck cabin are another source of fuel load. In a goods vehicle, the combustible items include tyres, mud guards, bumpers, seats, the instrument panel, cabin internal lining etc. Specifications from truck manufacturers have been used to identify the type of material for the construction of goods vehicles. Based on the above considerations, the simulation model for a LGV and HGV are shown in Figure 5.

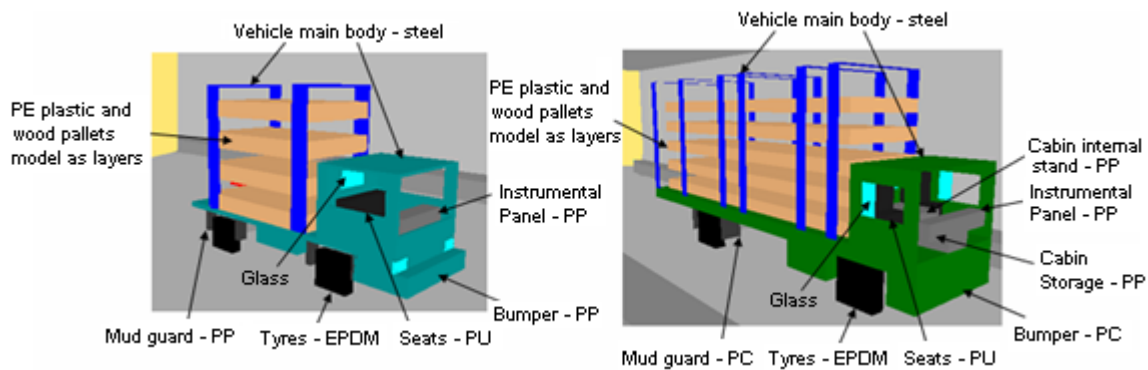


Figure 5: Material define for light goods and heavy goods vehicle simulation.

Tunnel geometry

The re-radiation effect in the tunnel will indirectly affect the heat release rate. Tunnels with smaller cross sectional areas tend to produce higher heat release rates as compared to tunnels with larger cross sectional areas and generally a wider tunnel is a safer tunnel [22]. However, the situation can be reversed when there is no ventilation provision in the tunnel. Without the supply of air, the condition can change to a ventilation controlled situation in view of smaller space that hinders combustion of the fuel. It is common to have slip road connecting the main tunnel to the open ground road. Very often the tunnel section for slip road is smaller than the main tunnel. The simulation for this tunnel has considered the effect of different cross sectional area along the tunnel alignments to ensure that the above phenomena are captured in the analysis.

Ventilation condition

The concept of blowing air into the tunnel is to provide a smoke free path for evacuation. However, there are concerns that this airflow will also fan the fire yielding higher heat release rate or flame spread to other vehicles resulting in larger fire size. From tunnel fire experiments [18] it has been observed that tunnel with higher airflow tend to fan the fire resulting in higher heat release rate. The presence of forced ventilation can increase the intensity of the fire due to the additional supply of oxygen [23]. On the contrary, it may also reduce the fire severity due to

cooling effects. There are also other effects such as opposed flow and wind-aided flame spread over the solids which can increase or reduce the rate of fire spread on the incident vehicle.

The velocity in the tunnel can vary depending on location of the tunnel and the mode of the tunnel ventilation. In a tunnel fire incident, the ventilation condition in the tunnel is changing, particularly at the early stage of the fire incident (change of ventilation mode to facilitate motorist's evacuation and fire service fire fighting). There may be instances where the tunnel fans are operating in a congestion mode due to traffic congestion and a fire occurs in the tunnel or a normal mode where the tunnel fans are turned off and a there is a tunnel fire. The operation modes of the above mentioned events are different resulting in a different airflow at different moments in time. These changes in airflow may have an effect on the heat release rate in the tunnel. Scenarios considering the detection time, operator reaction time and time required for the change of fan operational mode were considered in the simulation (Figure 6).

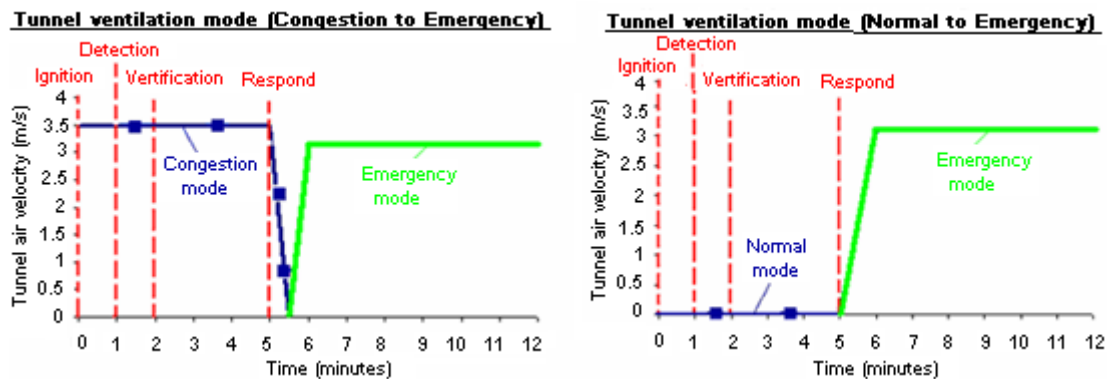


Figure 6: Examples of tunnel ventilation fan operating scenarios.

Ignition location

The location of fire ignition could affect the heat release rate curve [16]. Fire spread to the rear of the vehicle is delayed due to the ventilation in the driving direction resulting in lower heat release rate at the initial phase of the fire development. Fire ignition at the front and rear of the goods vehicles were simulated to consider this factor.

Fuel spills

One of the limitations is the petrol in the fuel tank was not included in the simulation. In a vehicle collision, there is a possibility of a fuel tank rupture resulting in a liquid fuel spill to the incident and neighbour vehicle. The flow rate from the rupture fuel tank can vary depending on the opening of the damage fuel tank, the area of resulting patch of liquid fuel on the road tunnel surface is related to the rupture fuel tank flow rate. When the flammable liquid fuel ignites, the heat release rate can vary depending on the diameter of the pool fire on the surface of the road tunnel.

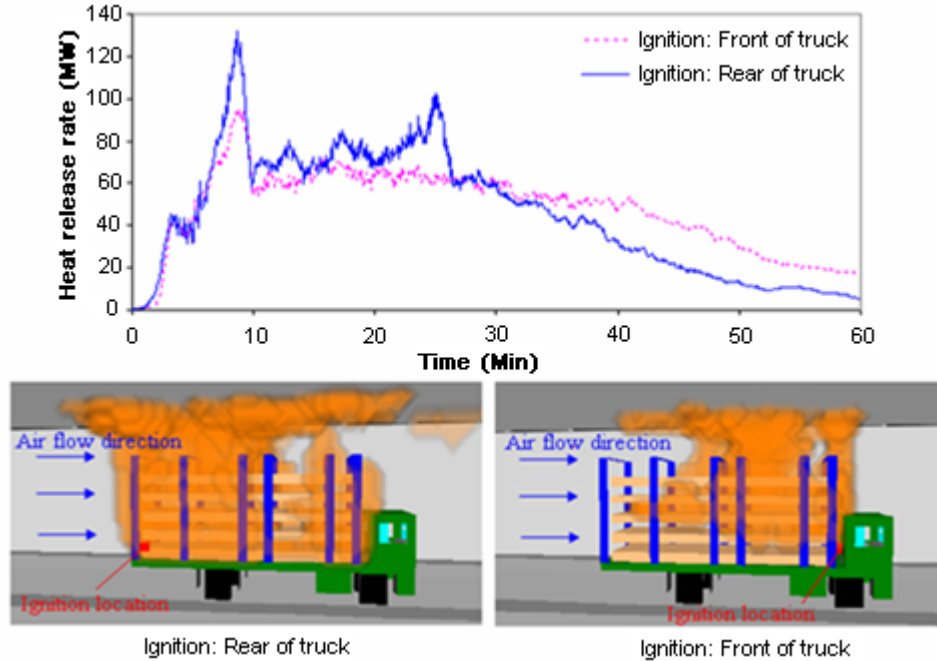


Figure 7: HGV [Time = 162 sec at $u = 2.9$ m/s]

Based on the above conditions, the number of scenarios involved can be numerous. There are also other factors such as tunnel gradient which can affect the direction and flow of the spillage. When the liquid fuel burns, the flaming liquid fuel may be flowing down slope and this is different from the approach used to model a solid material fire for this study. A new simulation approach considering the liquid fuel movement while burning will need to be examined which is beyond the scope of this study. For this case study, the tunnel is provided with a drainage system that is protected by detectors and automatic foam systems at the petrol interceptors. When such event occurs, the drainage system is design to quickly capture the spillage petrol so that its spreads will be limited and indirectly reduces the fire risk due to fuel tank rupture.

Simulated heat release rate

A total of 35 simulations were performed to establish the design fire which is considered as reasonable worst case. Various scenarios concerning tunnel geometry, fuel load, ventilation condition and ignition location related to this tunnel were simulated. The effect of glass breakage was also model in the simulation to capture the burning behaviour in the truck cabin. Transient simulations were performed by considering events of fire detection, operator response (e.g. operating the tunnel fans) and fans start up time in the simulation. In view of the number of simulations involved, only exemplar simulated heat release curves are presented.

The following observations have been made:

- i) Close examination of fire scenarios with the ignition source at the rear and front of the vehicle can effect the fire development. It has been observed that with the aid of the air flow in the tunnel; fire ignited at the rear of the vehicle seems to spread faster as compared to fire ignited at the front of the vehicle. A lower heat release rate was observed with ignition at the front of the vehicle as compared to scenario with ignition at the rear.

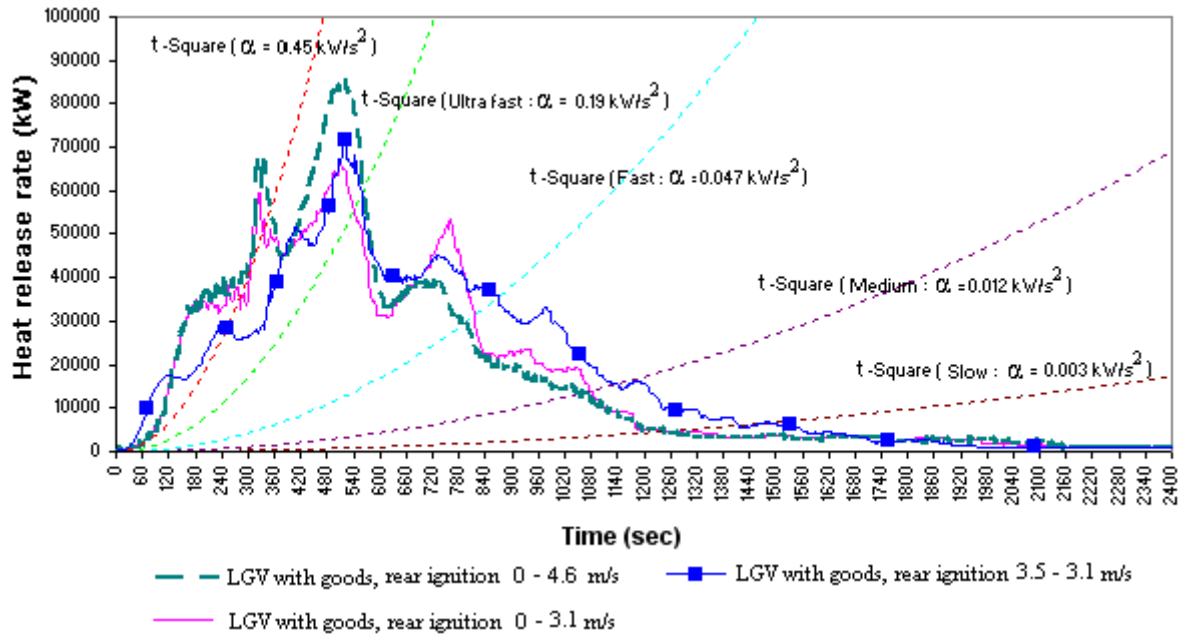


Figure 8: Comparing LGV heat release rate with different growth rate in a 3 lane tunnel.

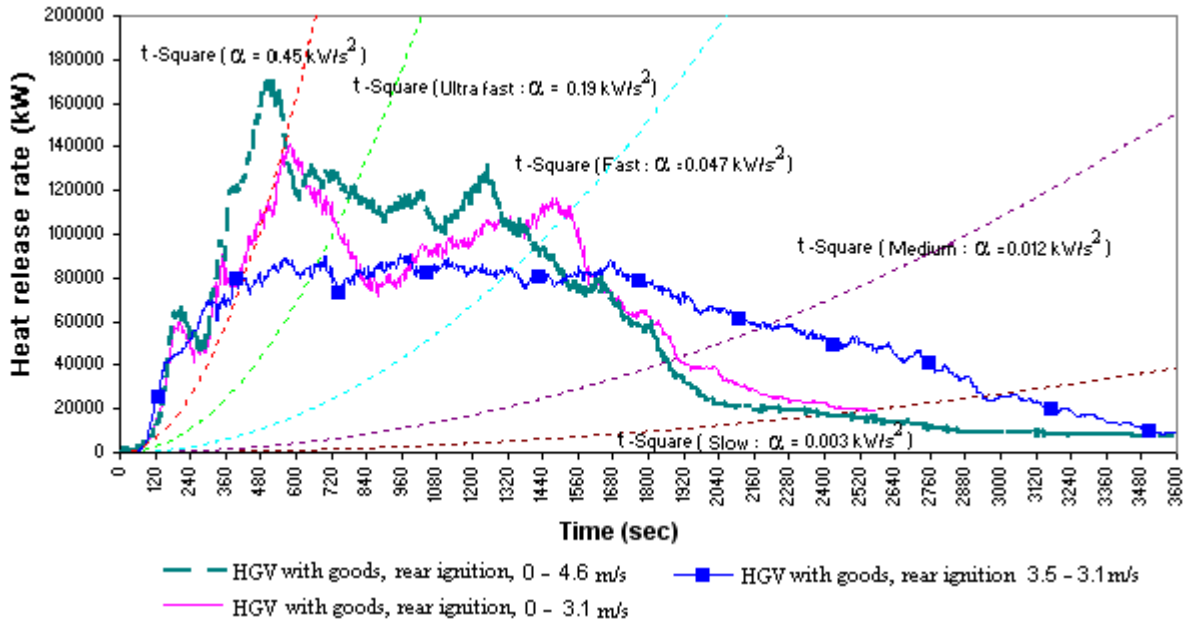


Figure 9: Comparing HGV heat release rate with different growth rate in a 3 lane tunnel.

- ii) There is an increase in peak heat release rate when tunnel velocity increases (Figures 8–9).
- iii) Operating the tunnel ventilation at the early stage of the fire development helps to reduce the severity of the fire during the growth phase (Figures 8–9).
- iv) A fire growth rate ($\alpha = 0.45 \text{ kW/m}^2\text{s}^2$) greater than the standard Fast growth has been observed for a goods vehicle fire in a two and three lane tunnel (Figures 8–9).

Figure 10 is a scatter plot showing the Peak Heat Release Rate (MW) on the Y-axis (ranging from 0 to 200) versus Fire Scenarios on the X-axis (ranging from 0 to 23). The data points are categorized by vehicle type and ignition location, as indicated by the legend:

- Single LGV fire without goods (Orange diamond)
- Single LGV fire carrying goods at slip road (Orange triangle)
- Single LGV fire carrying goods at main tunnel (Orange square)
- Single HGV fire without goods (Blue diamond)
- Single HGV fire carrying goods at slip road (Blue triangle)
- Single HGV fire carrying goods at main tunnel (Blue square)

Each data point is labeled with its corresponding wind speed and ignition location (e.g., 0 - 5.2m/s (RI)). The plot shows that the peak heat release rate generally increases with the fire scenario number, with HGV fires carrying goods at the main tunnel (blue squares) reaching the highest values (up to 190 MW).

CONCLUSION

An approach using risk analysis coupled with numerical analysis to establish a credible vehicle fire for smoke control design in a road tunnel has been developed. As each tunnel is unique, depending on the country, its regulatory requirements and the expected use of the tunnel, results from the fire risk analysis can vary. It is essential to collate sufficient statistical data on fire incidents, traffic data and vehicle population to identify the reasonable worst case fire scenarios.

The ventilation condition in the tunnel could have a significant impact on the heat release rate. Generally, higher air velocity would result in a higher heat release rate. With the aid of the tunnel air flow, a fire ignited at the rear of the vehicle appears to spread faster as compared to fire ignited at the front of the vehicle yielding higher heat release rate. In this illustration, when a single LGV or single HGV fire occurs in the tunnel, it is more likely to be fuel controlled rather than ventilation controlled due to the high flow rate generated by the tunnel ventilation fans.

The quantity of fuel load can significantly affect the fire size in the tunnel, a LGV would have a much lower heat release rate as compared with a HGV because the amount of goods carried is control by laden weight of the goods vehicle. The analysis in this study show the heat release rate can varies from 54 MW to 88 MW for a single LGV fire and 75 MW to 193 MW for a single HGV fire. The fire size varies depending on factors such as tunnel geometry, ventilation condition and ignition location of the fire.

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